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Mathematical Modelling of Surface Roughness in Turning of Stainless Steel (304 L) using Rayleigh's Method

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Abstract: In machining processes, surface roughness of the machined part is the major quality related issue. Not much work hitherto has been reported for modeling the surface roughness (Ra) in machining of Stainless Steel (304 L). This paper deals with the effects of process parameters like cutting speed, feed rate and different cooling conditions (i.e. dry, wet and liquid nitrogen used as a coolant) on surface roughness in machining of Stainless Steel (304 L) using uncoated tungsten carbide insert tool. The results from Taguchi approach have been used for developing a mathematical model for Ra; using dimensional (Rayleigh's method) and multiple linear regression analysis. The present results show that cryogenic machining processes can be implemented to minimize the surface roughness characteristics, thus the quality level of final product should be improved. The comparison with observational results will also serve as further validation of the model.
Keywords: Surface roughness, spindle speed, feed rate, Taguchi approach etc.

I. INTRODUCTION

Today's, a major needs in machining are the high material removal rate, low tool wear and lower surface roughness [1]. The major problems in achieving high productivity and quality are caused by the high cutting temperature developed during machining at high cutting velocity and feed rate [2]. During metal cutting operations heat is generated due to (i) deformation of metal, (ii) sliding friction of the chip at the tool rake surface, and also (iii) the friction between the workpiece and the tool flank. This heat increases the temperature of the tool and reduces its hardness and hence tool life. High temperature may also cause some adverse effects like dimensional inaccuracy, poor surface finish, etc [3-4]. The other factor i.e. tool life plays a major role in increasing the productivity [5]. Metals, especially alloy steels are the mostly used materials in the industry today. Functional metal parts can be produced in many ways as for example by casting, metal forming, sintering and machining with each process having its own advantages and disadvantages. During machining, the performance of cutting tool is higher if the cutting edge of the tool can be used for longer time [6]. Due to tool wear, the tool has to be turned or changed so that a fresh edge can be used [5] which leads to increase in production time and cost.

The tool may be cheap, but to turn it means to interrupt the machining process, which costs time and therefore money [6]. The two most commonly used tool materials to perform machining operations are coated/uncoated carbides and high speed steel. The tools have to withstand high temperature and stress during turning; they have to be shock resistant during milling, corrosion resistant and chemically inert towards the work piece material [6]. The most popular approach towards reducing the heat generated during cutting is by far, by employing cooling mechanism.

The cutting conditions in metal cutting can be improved by the use of cutting fluids, acting both as a coolant and a lubricant [7-8]. Different types of cooling methods are used to overcome temperature rise. Among them, the use of emulsion fluid is the most popular cooling method, mainly because of economy and ease of use [9]. However, the main problem with the conventional coolant is that it does not reach the real cutting area. The extensive heat generated developed from the tool chip interface evaporates the coolant before it reaches the cutting area. Hence heat generated during machining is not removed and is one of the main causes of the reduction in tool life [10].

Therefore the in this paper the new cooling approach is investigated to overcome this problem i.e. cryogenic cooling in which the liquid nitrogen is used as a coolant. The literature review reveals that a lot of work (experimental and theoretical) has been reported on different machining parameters using various cooling conditions. But not much work hitherto has been reported for modeling the surface roughness (Ra) in machining of Stainless Steel (304 L). The main objective of this study is:

1) Evolution of mathematical models for surface roughness using Rayleigh's method and multiple linear regression analysis.

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II. METHODLOGY

The levels of spindle speed (as 315 RPM, 500 RPM, 775 RPM), feed rate (as 0.179 mm/rev, 0.205 mm/rev, 0.248 mm/rev), cooling conditions (as dry, wet, cryogenics) and depth of cut (as 1 mm) were selected for machining Stainless Steel (304 L) based upon industrial application. Cooling conditions 1 represents dry condition, 2 represents wet conditions and 3 represents cryogenic conditions [i.e. Liquid nitrogen (LN_2)] were used as coolants. For this experimentation, a Kirloskar made center lathe with step variable spindle speed and feed was used. The headstock was powered by an AC motor and incorporated with a 3-jaw chuck to hold the work piece. Revolving tail stock center was used at the other end to support the work piece as shown in fig. 1. Stainless Steel (304 L) workpiece having initial diameter 58mm and length 200mm was turned in a Kirloskar made lathe by uncoated carbide insert of 0.4 mm nose radius. In this new approach the liquid nitrogen at atmospheric pressure was used as a coolant for machining purpose. A coolant pump with the coolant tank setup is employed. Essentially, in the wet machining, an oil based conventional coolant is applied which is supplied by the same nozzle that is utilized for the cryogenic fluid supply as shown in fig.2.

Fig. 1 Coolants used at tip of the tool

Fig. 2 Measurement of surface roughness

Cryogenic cooling is an external cooling method making use of a tube with an interior diameter of 1.5 millimeter. The stream of liquid nitrogen from the nozzle was targeted at the rake face along the main cutting edge of the tool. The liquid nitrogen jet coming along the primary cutting edge is supplied primarily to protect the rake face and the principal flank surface. Liquid nitrogen was used in the jet form flowing from a snout at a predetermined rate of flow of 0.36lt/min. After experimentation, a surface roughness tester was used to measure the surface roughness. Table 1 and 2 shows control log of experimentation (based upon Taguchi L9 O.A) and experimental observations for Ra as shown in fig. 3 [11]. Further the experiment has been repeated three times to reduce experimental error. The relationship between Ra and main controllable process parameters are shown in fig. 4. From these given factors, we chose only three independent variables on which Ra is depended i.e. spindle speed (V), feed (f) and cooling conditions (θ).

Table 1 Three levels and three parameters for Taguchi L9OA

Sr. No.	Spindle speed	Feed rate	Cooling Conditions
1	775	0.179	Dry
2	500	0.205	Wet
3	315	0.248	Cryo

Table 2 Observations of final experimentation

Sr. No.	RPM (V)	Feed (f)	Cooling Conditions	Surface Roughness (Ra)			S/N ratio
				R1	R2	R3	
1	775	.179	Dry	3.14	3.12	3.17	-9.93859
2	775	.205	Wet	2.37	2.33	2.38	-7.49497
3	775	.248	Cryo	1.10	1.05	1.15	-0.82785
4	500	.179	Wet	2.14	2.13	2.17	-6.60828
5	500	.205	Cryo	1.13	1.11	1.12	-1.06157
6	500	.248	Dry	3.2	3.0	3.3	-10.103
7	315	.179	Cryo	1.2	1.10	1.23	-1.58362
8	315	.205	Dry	4.5	4.47	4.51	-13.0643
9	315	.248	Wet	4.04	4.01	4.08	-12.1276

III. RESULTS AND DISCUSSION

A. Mathematical Modelling Of Ra

As per Taguchi design, Ra in machining of Stainless Steel (304 L) was significantly depend on tool work interface temperature i.e. cooling conditions. The values of percentage contribution of input parameters and geometric model for response Ra are shown in Table 3 & 4 respectively. The work under consideration deals mainly with obtaining optimum system configuration in terms of response parameters with minimal expenditure of experimental resources [12]. The best settings of control components have been found through experiments.

B. Rayleigh's method

Dimensional analysis is a mathematical technique deals with the dimensions of physical quantity and further used for conducting model tests. In this new approach surface roughness analysis through Rayleigh's method and multiple linear regression are used for developing the relations.

Rayleigh's method is applied for defining the expression for a variable which depends upon maximum three or four variables only. Since, Ra is variable, which depends on input levels namely; spindle speed, feed rate and cooling conditions respectively, therefore by selecting basic dimensions:

1) M (mass);
2) L (length);
3) T (time); and
4) θ (temperature).

The given dimensions of forgoing quantities are in following:

a) The "Ra" (um): L
b) Cooling conditions "θ" (°C): θ
c) Spindle speed "V" (RPM): T^{-1} (min)
d) Feed rate "f" (mm/rev): LT

Then according to Rayleigh's method, Ra is function of V, f and θ. Mathematically, the equation can be written as can be written as:

$Ra = K.\ V^a.\ f^b.\ \theta^c$ (1)

Where K is constant and V, f and θ are speed, feed and cooling conditions. Substituting, the dimensions of each term in Equation 1.

$L = K.\ T^{-1a}.\ LT^b.\ \theta^c$ (2)

Thus, by solving mathematical equation 2, we get

$Ra = K.\ V.\ f.\ \theta$ (3)

It has been experimentally found that Ra directly goes with V, f and θ.

C. Multiple Linear Regressions

The dependent variable Ra be considered as a linear combination of the independent variables, namely spindle speed (v), feed rate (f) and cooling conditions (cc). To determine the coefficients of equation, least square method is taken in multiple linear regression analysis. The following general equation can be obtained:

$Y = A + B_1 v + B_2 f + B_3 cc$ (4)

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Where Y is the dependent variable or corresponding response i.e., Ra, *A* is constant called the intercept of the plane, B_1, B_2 & B_3 are the regression coefficients depends upon main parameters. The given equation is called multiple linear regression model with three independent variables. The term R^2 called as the coefficient of determination is commonly taken to evaluate the adequacy of regression models developed [13]. The range R^2 may be written as $0 \leq R^2 \leq 1$. When R^2 value approaches to unity, it is used up as better prediction of responses and fitting of the model with the data. If R^2 value is 85%, it signifies that this model explains about 85% of the variability in predicting new observations. Furthermore, analysis of variance and normal probability plot has also been used to examine the significance of regression model developed [14].

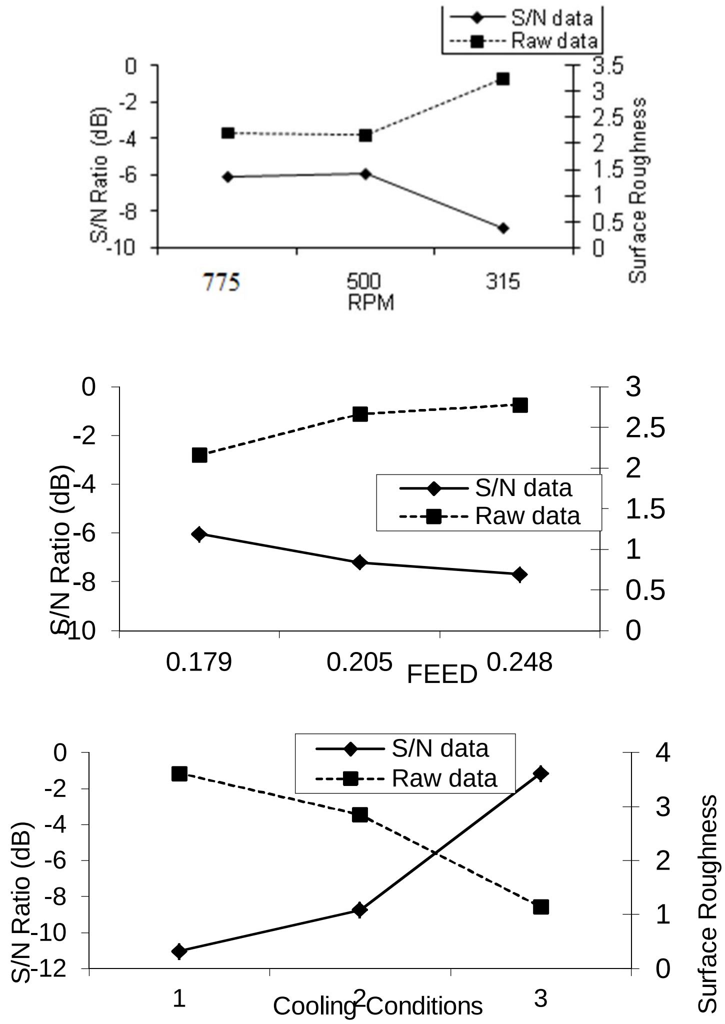

Fig. 3 Variation of S/N ratio Surface roughness w.r.t. RPM, feed & cooling conditions

[Note: Cooling conditions 1 signifies dry, 2 signify wet and 3 signifies cryogenic cooling]

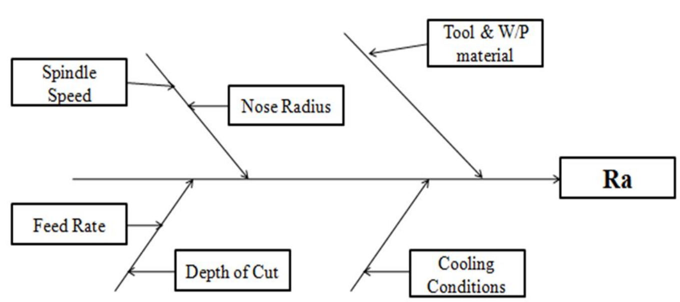

Fig. 4 Cause and effect diagram of Ra

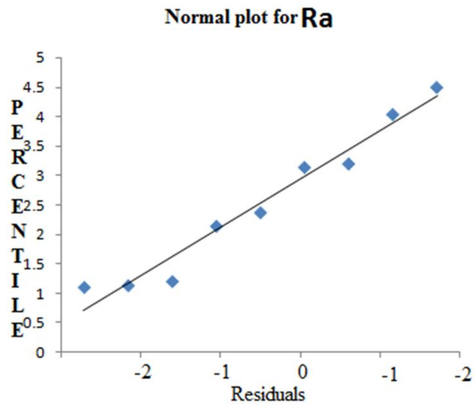

Fig. 5 Normal probability plot of the residuals for Ra

By using the least square method to the observational data (Table 3), following regression equation is obtained for Ra:

Ra = 4.3494 – 0.00208*v* + 8.3484*f* – 1.235*cc* R^2 = 85.44% (5)

From analysis of variance Table 5, as P-value is less than 0.05 at 95% significance level, it is revealed that the regression model for Ra (Eq. (5)) is significant. Mathematical models showed high determination coefficients explaining 85.44% variability for Ra. The predicted value and the experimental values are really close to each other with less residual (Table 6) for both the examples showing the significance of the models produced. Further, the N-plot is used to control the residual error. If the residual lays approx along the straight line, then normality assumption is satisfied. N-plot was described based on Ra shown in fig. 5 the value shows that the residual lies close to the straight line, therefore error are distributed normally and the results are significant.

Table 3 ANOVA & Percentage contribution for Ra

Parameters	Sum of square	Mean Square	F value	Percentage contribution	Remarks
RPM (V)	17.08625	8.543126	6.350466	9.264682	Significant
Feed rate	4.281574	2.140787	1.591337	2.321599	
Cooling conditions	160.3651	80.18257	59.60308	86.95482	Significant
Error	2.690551	1.345276		1.458898	

Table 4 Geometric model for Ra

Optimized Ra conditions	
Spindle Speed	500 RPM
Feed rate	0.179 mm/rev
Cooling conditions	as 3 i.e. Cryogenic cooling conditions

Table 5

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	11.05043599	3.683478664	9.781988537	0.015590479
Residual	5	1.88278623	0.376557246		
Total	8	12.93322222			

ANOVA for Ra model

Table 6 Experimental vs. predicted value

Sr. No.	Experimental Ra	Predicted Ra	Residuals Ra
1	3.14	2.99648645	0.14351355

2	2.37	1.97854565	0.39145435
3	1.10	1.102528174	-0.002528174
4	2.14	2.333601087	-0.193601087
5	1.13	1.315660287	-0.185660287
6	3.2	4.144642811	-0.944642811
7	1.2	1.483478206	-0.283478206
8	4.5	4.170537406	0.329462594
9	4.04	3.29451993	0.74548007

IV. CONCLUSIONS

Experimental observations reported in this study suggest that the use of cryogenic coolant in machining of alloy steel STAINLESS STEEL (304 L) significantly affects the surface roughness. In particular cryogenic cooling conditions, it offers best surface roughness as compare to dry and wet machining. The following conclusions may be drawn from the results of this research.

A. Rayleigh's method and multiple linear regression analysis are used for mathematical modeling.
B. Mathematical models for flank wear and surface roughness are statistically significant as P-value is less than 0.05 at 95% significance level. The models presented high determination coefficients (R^2) explaining 85.4% variability for surface roughness. It shows high significance of the model developed.
C. A result shows that, cooling conditions, i.e. cryogenic cooling provides maximum contribution and significantly affects the Ra.
D. Value from N-plot was described, which shows that the residual lies close to the straight line, therefore error are distributed normally and the results are significant.
E. Based on these results, the surface roughness improvement is 7.84%.

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